

# Design for Maximizing RHA Penetration of Yawed Penetrators

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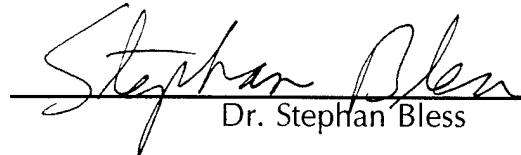
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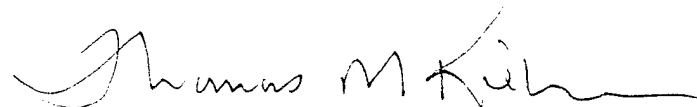
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# Design for Maximizing RHA Penetration of Yawed Penetrators

Minhyung Lee

## 1.0 OBJECTIVE

If a long rod penetrator impacts a target at a high yaw angle, interference of the penetrator with the sidewall of the crater degrades penetration performance [1].

The objective of this work is to analyze the penetration performance of an anti-armor kinetic energy penetrator with increased RHA penetration during yawed impact. Two penetrators are proposed: a variable diameter penetrator and a variable density penetrator.

## 2.0 TECHNICAL APPROACH

Figure 1 defines the basic parameters of both a variable diameter rod (frustrum) and a simple rod of the same material. A large head diameter offers the potential to exploit the increase in P/L since it can create an enlarged cavity entrance diameter, thus resulting in increased critical yaw angle below which penetration is unaffected. The proposed penetrator and the simple rod have the same mass, length, and therefore the same kinetic energy at the same impact velocity. We also examine the penetration degradation of different density materials of the same kinetic energy and length.

## 3.0 PROPOSED PENETRATORS

### 3.1 Design 1—Variable Diameter

In this study, the simple rod is defined by the following parameters:

material = tungsten alloy ( $\rho_p = 17.4 \text{ g/cm}^3$ )  
 $L/D_r = 35$   
 $D_r = 0.78 \text{ cm}$   
 $L = 27.3 \text{ cm}$

Since mass, length and material of the frustrum are the same as those of the simple rod, from the volume relation,

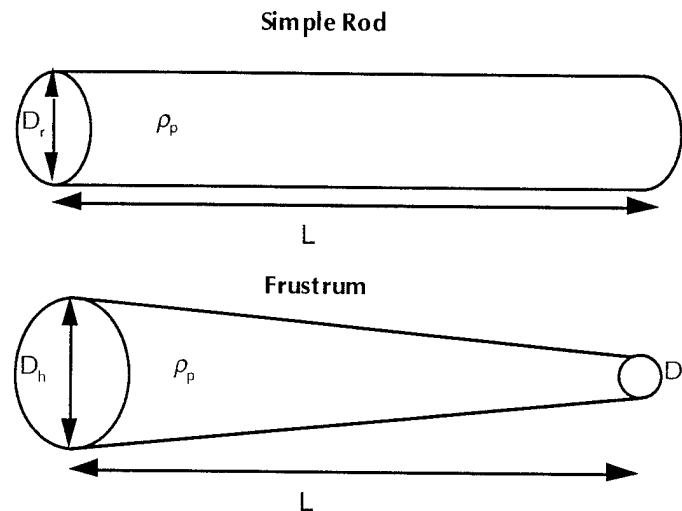
$$\frac{\pi}{4} D_r^2 = \frac{\pi}{12} (D_h^2 + D_h D_t + D_t^2), \quad (1)$$

we can define the parameters of the penetrators used in the analysis, as shown in Table I.

**Table I. Variable Diameter Penetrators**

| Parameters | Penetrators |      |       |
|------------|-------------|------|-------|
|            | 1           | 2    | 3     |
| $D_h/D_r$  | 1           | 1.35 | 1.7   |
| $D_h/D_t$  | 1           | 2.24 | 27.24 |

For the purpose of obtaining some insight into the design of a penetrator, we select 1.7 for the value of  $D_h/D_r$ . This is essentially the largest possible value, because when  $D_h/D_r = \sqrt{3}$ ,  $D_h/D_t = \infty$ .



**Fig. 1. Notation for Design 1 penetrators.**

### 3.2 Design 2—Variable Density Rods

Consider a family of rods that have the same kinetic energy at the same impact velocity, mass and length; that is,  $\rho_p D^2$  is constant, yielding different values of  $L/D$ . The reference penetrator material is taken as RHA with  $L/D = 20$ . Table II shows the penetrator parameters used in the analysis. The target material is RHA.

Table II. Variable Density Penetrators

| Parameters                    | Penetrators |      |          |
|-------------------------------|-------------|------|----------|
|                               | Aluminum    | RHA  | Tungsten |
| $\rho_p$ (g/cm <sup>3</sup> ) | 2.77        | 7.86 | 17.4     |
| Diameter (cm)                 | 1.31        | 0.78 | 0.52     |
| L/D                           | 11.9        | 20   | 29.8     |

#### 4.0 ANALYSIS

##### 4.1 Critical Yaw Angle

A yawed long rod penetrator of density  $\rho_p$ , diameter  $D_r$ , and length  $L$  impacts at normal incidence an infinite target of density  $\rho_t$ . The critical yaw is defined as the value of impact yaw where the tail of the penetrator just touches the sidewall of the cavity entrance. The expression for this angle is given by [2],

$$\theta_c = \sin^{-1} [(D_c - D_r)/2L], \quad (2)$$

where  $D_c$  is the cavity entrance diameter which can be obtained from the momentum principle and is given by [3],

$$D_c = D_r \sqrt{\frac{Y_p}{R_t} + \frac{2\rho_p(V-U)^2}{R_t}}, \quad (3)$$

where  $Y_p$  is the dynamic yield strength of the penetrator and  $R_t$  is the target resistance for radial cavity expansion.  $V$  and  $U$  are the impact and penetration velocity, respectively. From the modified Bernoulli equation  $U$  is given by [4],

$$U = \frac{V - \alpha \sqrt{V^2 + 2(1 - \alpha^2)(R_t - Y_p)/\rho_t}}{(1 - \alpha^2)}, \quad (4)$$

where  $\alpha = \sqrt{\rho_t/\rho_p}$ . The theoretical  $R_t$  value for RHA used in this work is 5 GPa. By combining Eqs. (2) and (3), the critical yaw for a tungsten alloy penetrator impacting RHA at normal incidence can be obtained from its geometry and impact velocity alone.

The critical angle as a function of impact velocity and ratio of the head diameter to simple rod diameter is shown in Fig. 2 for Design 1 penetrators. The critical yaw angle for each penetrator increases with impact velocity due to the



increase in the cavity entrance diameter. The critical yaw angle increases as the  $D_h/D_r$  increases. This can be explained by two facts: the increased cavity entrance due to increased head diameter and the decreased tail diameter which reduces the chances of colliding with the sidewall of the cavity entrance. For example, at 2.6 km/s the critical yaw angle is increased about 250 percent by changing the values of  $D_h/D_r$  from 1 to 1.7.

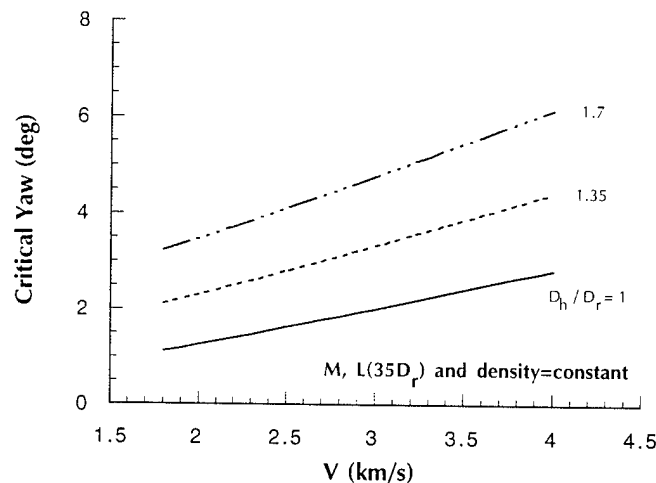


Fig. 2. Critical yaw versus velocity, tungsten alloy striking RHA.

The critical angle as a function of impact velocity is shown in Fig. 3 for Design 2 penetrators. It can be seen that the critical yaw angle increases with lower density rods. This is a consequence of the fact that lower density rods have a lower penetration velocity which, in spite of constant  $\rho_p D_r^2$ , is responsible for an enlarged cavity diameter, as calculated from Eq. (3).

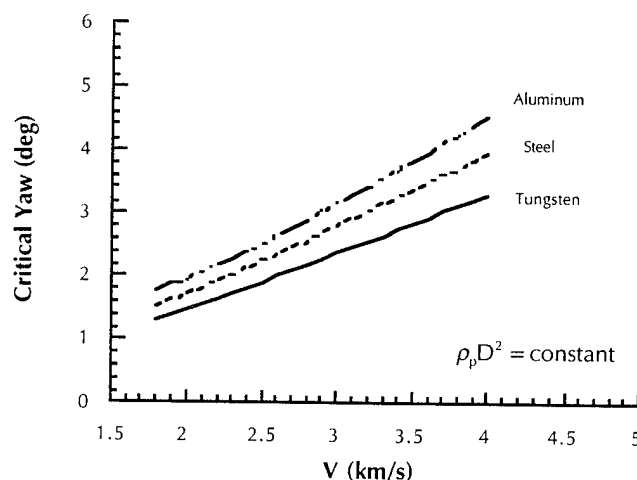


Fig. 3. Critical yaw versus velocity for Design 2 penetrators.

## 4.2 Penetration Degradation

Thus far, the threshold yaw values beyond which the penetration performance is degraded are provided in two design cases. In this section, each case of penetration performance is examined and compared to one another. To achieve this, we propose a simple model with a degradation constant which is determined from correlation with the empirical equation obtained by Bjerke et al. [1]. Note that the data used for obtaining the empirical equation consisted of ductile tungsten alloy penetrators.

From the modified Bernoulli equation, the constant penetration rate can be obtained by

$$s = -\frac{\Delta P}{\Delta L} = \frac{U}{V-U} = \frac{-\varphi + \sqrt{\varphi + \alpha^2(1-\varphi)}}{\varphi + \alpha^2}, \quad (5)$$

where,

$$\varphi = \frac{(R_t - Y_p)}{1/2\rho_p V^2}. \quad (6)$$

Once an impact has occurred, we presume that the penetration by the upstream portion ( $L_u$ ) of the penetrator is unaffected, and the penetration by the downstream portion ( $L_d$ ) is degraded (see Fig. 4). The penetration depth with yaw can then be expressed by,

$$P = \begin{cases} L s & \theta \leq \theta_c, \\ L_u s + L_d \beta(\theta) s & \theta > \theta_c, \end{cases} \quad (7)$$

where  $\theta_c$  is the critical angle and  $\beta(\theta)$  is a degradation constant. Using geometric relations,  $L_u$  is given by,

$$L_u = (D_c - D_r) / (2 \sin \theta), \quad (8)$$

and  $L_d$  is equal to  $L - L_u$ . Since normalization can eliminate the influence of velocity and aspect ratio of the penetrator, the ratio (referred to as effective penetration) is then,

$$P_e = \frac{L_u}{L} + \beta(\theta) \frac{L_d}{L}. \quad (9)$$

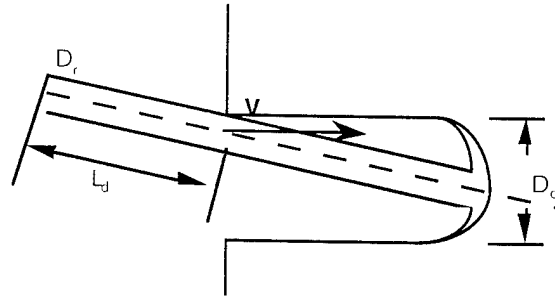


Fig. 4. The geometry of the sidewall impact for rods.

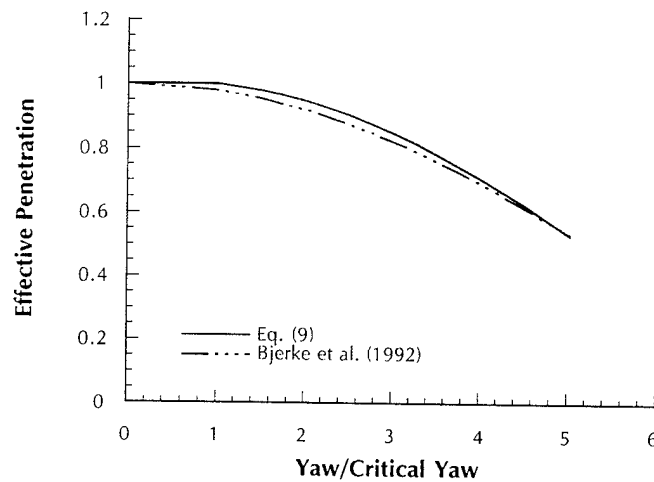


Fig. 5. Normalized penetration versus normalized yaw.

Correlating Eq. (9) with the empirical data, valid up to five times the critical yaw given in Ref. [1], enables us to determine the degradation constant given approximately by,

$$\beta(\theta) = \cos(13\theta / \theta_c). \quad (10)$$

It is important to remember that this equation is not general but may be dependent upon the projectile and target materials. Nevertheless, it should be sufficient to achieve the essential penetration performance associated with yawed impact. In Fig. 5, the normalized penetration result is shown as a function of normalized yaw angle. The result obtained from Eq. (9) is also plotted and compares well with the empirical equation. In order to see the effect of impact velocity on the penetration degradation, the effective penetration is plotted as a function of yaw in Fig. 6. Penetration performance increases with impact velocity at the same yaw angle.

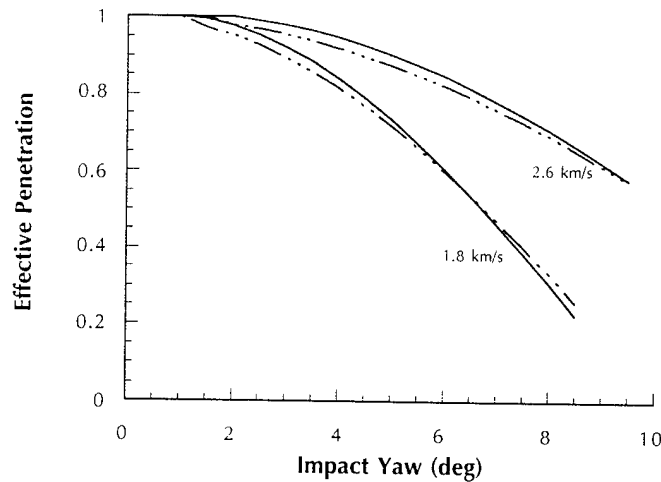


Fig. 6. Normalized penetration versus normalized yaw, tungsten alloy ( $L/D = 30$ ) striking RHA.

Now Eq. (9) is used to determine the penetration efficiency for the proposed penetrators. Figure 7 shows the effective penetration as a function of yaw for Design 1 penetrators striking RHA at 2.6 km/s. It can be seen that the penetration efficiency for the penetrator of  $D_h/D_r = 1.7$  is less sensitive to yaw as impact velocity increases.

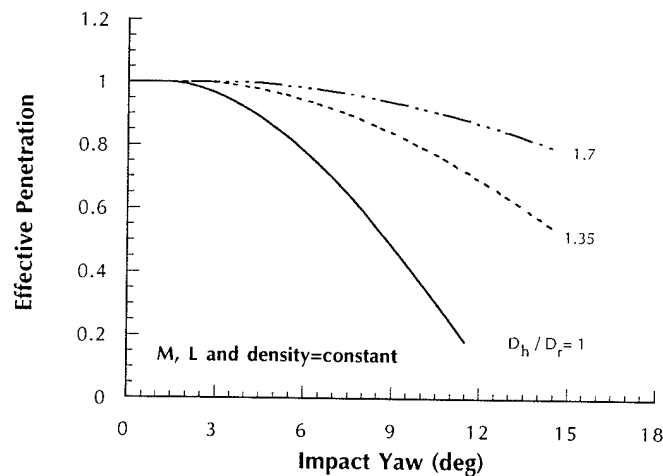


Fig. 7. Normalized penetration versus yaw, tungsten alloy ( $L/D_r = 35$ ) striking RHA at 2.6 km/s for Design 1.

For Design 2 penetrators striking RHA at 2.6 km/s, the penetration as a function of yaw is plotted in Fig. 8. Although the tungsten rod has a small value of critical impact yaw, the penetration depth is larger than lower density rods up to  $12^\circ$  yaw impact. Beyond this angle the penetration becomes the same, or even less, than lower density rods since high density rods are sensitive to yaw.

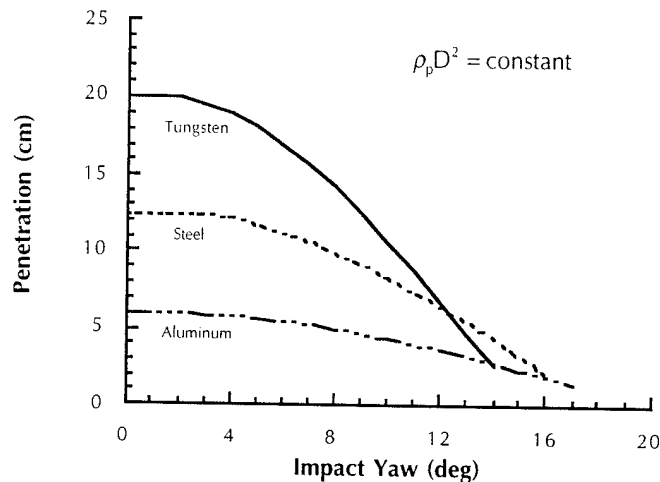


Fig. 8. Penetration versus yaw for Design 2 penetrators striking RHA at 2.6 km/s.

## 5.0 SUMMARY AND RECOMMENDATIONS

As a result of this work, frustum penetrators (large head diameter) are viewed positively. The larger the head diameter, the larger the crater size. However, it is required that the proposed penetrators should be launchable (L/D and stiffness). It is not known whether or not the relative ease of supporting tapered penetrators with a sabot will compensate for their inherent structural weakness. The Design 2 analysis presented here suggests that use of a higher density rod can significantly increase RHA penetration at the same kinetic energy and length up to a certain yaw angle. A negative aspect of a higher density rod is that it has a greater L/D than a lower density rod, thus resulting in more buckling or deformation of the rod during launch.

It is obvious that a key technical issue for designing a better anti-armor penetrator with yaw is to investigate the real physical mechanisms, for different materials, which interfere with the penetration process. To the best of our knowledge not a great deal is known about the effect of the resulting stress fields, including transient tensile and bending waves on penetration degradation with yaw.

As mentioned previously, the degradation equation is limited to the condition of ductile tungsten alloy penetrators impacting RHA targets, and up to five times the critical yaw angles. Thus, more effort should be initiated for examining various potential candidate materials.

## ACKNOWLEDGMENTS

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